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Renewable energy technologies in the Maldives—determining the potential

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Abstract

The Maldives is one of the most vulnerable countries to the projected impacts of climate change, due to a combination of the small sizes of the islands and their low height above sea level. Like other small island developing states, the Maldives depends overwhelmingly on petroleum imports for their electricity production, which creates serious economic and financial difficulties. The Government of Maldives is therefore committed to promote sustainable energy and has been actively pursuing several inter-related initiatives to overcome the existing barriers to the utilization of renewable energy technologies. To assist this, the quantification and evaluation of the potentials of available solar and wind resources in the country for electricity applications has been performed. The hybrid system design tool HOMER has been used to create optimal renewable energy (RE) system designs. In order to evaluate these different RE alternatives a multi-criteria analysis is performed using a number of criteria that are likely to be decisive in implementation decisions. The evaluation shows that fully RE system configurations are not financially viable in the Maldives while the RE-diesel hybrid systems could bring down the price of electricity with 5–10 $cent/kWh in smaller outer islands. Assuming that these latter systems with a high probability of adoption are implemented, the results

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show that 10% of the electricity in the Maldives could be supplied by RE based systems in a cost effective way.

Keywords: Resource assessment; Renewable energy technology; Adoption; Multi-criteria analysis; Small island developing states; Maldives

Contents

1. Introduction

The Republic of the Maldives is blessed with abundant renewable energy (RE) resources, but depends overwhelmingly on petroleum imports for their electricity production. In fact, petroleum products account for more than 16% of the total imports in the Maldives. This creates serious economic and financial difficulties, similar to other Small Island Developing States (SIDS)[1]. The reason for this is that these SIDS are often very isolated and have high transport costs for fossil fuel imports. Furthermore, a limited demand for fuels domestically and diseconomies of scale in electricity production, makes power production not only extremely expensive but also bears financial risks on the long term [2,3]. As a consequence of this fossil fuel dependence, a sharp increase in the price of oil can cause severe macroeconomic consequences; deflationary, reducing demand for goods and services, thereby creating unemployment [4].

Also the environmental effects of fossil fuel use on a global scale are disastrous for SIDS since climate change and sea level rise will have dramatic implications for all coastal communities, and the increasingly intense nature of destructive weather systems will hit

islands particularly hard. According to the First National Communication of the Republic of the Maldives to the Nations Framework Convention on Climate Change (UNFCCC) by the Ministry of Home Affairs, Housing and Environment [5], the accelerated sea level rise will have devastating effects on the islands and can threaten the very existence of the country as a whole.

Of course small island states, like the Maldives, cannot directly influence global energy consumption, nevertheless they can diversify and develop their economies by utilizing their indigenous RE resources and by doing so they are an example to the world how renewable societies could be built up.

Although it is expected that the country will rely on imported fossil fuels for most of its energy needs in the coming years, RE sources, such as solar and wind are recognized as potential energy alternatives. These can supplant part of the imported fossil fuels and contribute to the goal of sustainable development. The Government of Maldives (GoM) is committed to promote sustainable energy by formulating policies on energy, including adaptation, promotion and implementation of Renewable Energy Technologies (RETs) in the Maldives. Developing appropriate measures now will secure the constant supply of energy in a more stable economy and serves the long-term goals on reducing greenhouse gas (GHG) emissions and improving the standard of living of the Maldivians [6]. We have performed an extensive study on the development of these measures and the results are reported in two papers[1], the present one and the accompanying paper [7].

In this paper we identify the RETs that have a high probability of adoption based on techno-economic and environmental criteria and we determine their potential to supplant part of the imported conventional energy forms that are currently used in the Maldives. We will evaluate fully renewable systems based on solar and wind energy and several hybrid configurations using a number of criteria that are likely to be decisive in implementation decisions. The probability of adoption refers to the case in which it is assumed that a technically feasible and economically viable technology is used in a competitive market and constraints such as consumer preferences, social, institutional and financial barriers to its usage do not exist [8]. These issues are addressed in the accompanying paper [7], which continues with the proposition that the realization of RE projects in the Maldives is not only depending on the techno-economic attributes of the technology itself, but is also influenced by its social, institutional and political context. Hereby we make use of an Innovation System approach, which is also suitable to analyse the lock in of fossil fuel in SIDS and explains why SIDS are still so dependent on fossil fuels and have not switched to RE sources by now.

This paper is organised as follows; first we will give an overview of the current energy situation in the Maldives, from which we have derived the boundaries for our analysis. Then a resource assessment and cost analysis are introduced in order to design optimal RE based systems for various case study islands. For the design we make use of the hybrid optimization model for electric renewables (HOMER, version 2.19) [9]. In order to

[1]The work we have done has contributed to the renewable energy programme of The Ministry of Environment, Energy and Water under UNDP assisted projects, namely the renewable energy technology development and Application (RETDAP) funded by the global environment facility (GEF) and the Energy Resource Assessment Project funded by UNDP and DANIDA. (http://www.mv.undp.org/projects/environment_energy1.htm) Furthermore this report has made a contribution to the SMILES project (strengthening maldivian initiatives for a long-term energy strategy) co-funded by the European Commission (EC) under the Asia Pro Eco Programme (http://www.mcst.gov.mv/projects/smiles/).

compare the different RE system alternatives with each other and select the option that has the highest probability of adoption on a specified location in the Maldives a multi-criteria analysis is performed using the software package DEFINITE [10]. We analyse the robustness of choice by different weighing factors for the criteria. These results are then put in a national perspective in order to determine the potential amount of fossil fuel based energy systems that could be supplanted by RETs if the optimal system configurations are implemented in the whole country.

The outcome of this analysis is of specific use for implementation decisions regarding RE in the Maldives and other SIDS but the methodology presented is useful in all adoption discussions regarding RE in developing countries.

2. Current energy situation

The Republic of the Maldives is comprised of 1192 small coral islands located to the South-East of India in the Indian Ocean. Only 199 islands are inhabited. The total population of the Maldives was 270 thousand in 2000 [11]. A quarter of the countries population resides in the capital Malé (4°N, 73°E), which is located in the centre of the republic and where most of the economic and commercial activities take place. The population density on most of the islands is very high. Nearly half of the inhabited islands have a population density over 2000 person/km^2. The large coral atoll chain of the Maldives is spread out over an area of about 100×700 km^2, while the total land area only is around 300 km^2. The sizes of the flat islands vary from 0.5 to 5 km^2. Around 85% of the inhabited islands have an area less than 1 km^2 [12]. Over the past twelve years, 89 islands have been developed into tourist resorts, demonstrating exploitation of the country's warm and humid tropical climate. The mean annual temperature and humidity are 28 °C and 80%, respectively. The rapidly growing upper class tourism industry has raised the standard of living of many Maldivians in the past years. The annual Gross Domestic Product (GDP) growth rate is between 7 and 9% in the last decade and the population grew with nearly 2% per year in that same period [11].

The change in the fuel mix from traditional natural energy sources (wind for sailing and wood for cooking) to fossil fuels in order to reach the growing energy demand has led to a steep increase of imported fossil fuels. With the construction of energy-intensive high-rise buildings and the penetration of household and commercial electrical appliances mainly on the island of Malé, the consumption of commercial energy in the Maldives has increased from about 74 Mtoe in 1994 to 213 Mtoe in 2004, indicating an average annual growth rate of 11%. The transport and electricity generation sector has contributed the most to this steep increase of fossil fuel use, but the fishery and tourism account for it as well [12]. The current energy supply mix, which is presented in Table 1, shows that the major share of these imported fuels is Diesel Fuel Oil (DFO), which is mainly used for electricity generation and as fuel in the transportation sector [13].

In 1990, one third of the population did not have access to electricity; by now the number is reduced to only 3%. In Malé alone the electricity generation has increased from 42 million kWh annually in 1994 to over 108 million kWh in 2003, representing a growth rate of nearly 12% per year [14]. Despite the rapid electrification of outer islands, the electricity consumption in the capital city is approximately five times higher than in outer islands. The amount of electricity that is consumed per capita in the Outer islands is between 175 and 350 kWh per year, while a citizen of Malé uses about 1300 kWh per year.

Table 1
Energy supply mix of Maldives in 2004 [13]

Energy carrier	Typical uses	Energy supply, Mtoe	
		Mtoe	%
Diesel Fuel Oil	Transport, Industries, Electricity generation	184.2	86.3
Gasoline	Transport	14.8	6.9
Kerosene	Lighting, Cooking	4.5	2.1
Aviation fuel	Air transport	0.8	0.4
LPG	Cooking, Industrial operations	5.7	2.7
Biomass (wood)	Cooking, Drying	3.5	1.6
Total		213.5	100

However, this is far less than the tourists are consuming on the 89 up-market resort islands in the country, which is on average 15400 kWh/bed/year. It is therefore no surprise that nearly half of the countries generation capacity of approximately 125 MW is installed on these resort islands [13].

The ongoing increase in electricity demand tends to catch up rapidly with the installed capacity every few years. This makes investments in new power plants necessary, which contributes to the high costs of electricity in the Maldives. The generators are built to meet the peak demand and the rest of the day the generators run at low loads, which is inefficient. In these cases the operation and maintenance costs are relatively high and are very often passed on to the users. Current prices[2] differ from US$ 0.15/kWh for residential use to US$ 0.25/kWh for businesses in Malé and the larger inhabited islands [12]. In the outer islands the prices are roughly twice as high. These prices strike hard in the low budgets of the majority of the people in the outer islands. The high prices are mainly caused by the high price of DFO that is used for electricity generation, which accounts for 70% of the costs[3] [14].

In order to lower the price the overall efficiency of the power plants could be improved through strategies aiming at higher generator, transmission and distribution efficiencies and the use of cogeneration techniques. In addition, a strategy other than only diesel power generation is needed and the potential of RE based systems should be assessed [12].

3. Demographic and technological restrictions

In order to assess the amount of fossil fuel based electricity generators that could be replaced by RE systems (under the restriction that the unit costs for electricity will not increase) five different type of islands have been studied in detail. These include the capital Malé and four outer islands that are different in size and therefore have a specific energy demand, see Table 2.

[2]The study described in this paper was performed in 2004, and prices stated are prices of that year. In 2004 the average oil price was 35$ per barrel [15].

[3]Therefore an increase in crude oil prices like we have experienced in the summer of 2005 with prices up to between $50–$60 per barrel [16] could lead to even higher unit costs of electricity.

Table 2
Characteristics of four outer islands [39]

Outer island	Location	Number of citizens/ households	Generator capacity (kVA)	Demand (kWh/day)
1: Fehendhoo	4.9°N, 72.9°E	245/40	10 + 25	100
2: Uligamu	7.1°N, 72.9°E	435/63	20 + 31	178
3: Nolhivaranfaru	6.7°N, 73.1°E	650/100	22 + 39	300
4: Hanimaadhoo	6.8°N, 73.2°E	1009/240	125 + 200	765

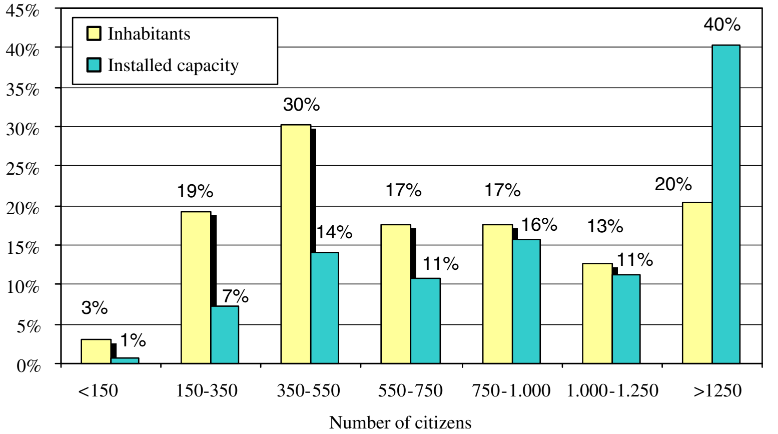


Fig. 1. Distribution of outer islands as a function of their population size and installed capacity. Note that 40% of the installed capacity on the outer islands is installed on the "Main islands" [33].

As shown in Fig. 1, these islands represent 80% of the Outer islands as most islands have the same size, population, governance and, more important, the same load pattern, which is comprised of domestic and commercial users. Energy demand depends on the amount of citizens, while also the demand per capita per day increases from 0.4 kWh/capita/day for Fehendhoo to 0.75 kWh/capita/day for Hanimaadhoo, see Table 2. Islands that have industrial users (i.e. more than 1250 citizens) do not fit these patterns and are therefore excluded from this study, because specific designs should be made to fit their individual load structure. From now on these islands will be referred to as "main islands", while the others are denoted as "outer islands".

Besides the demographic restriction this study focuses only on RETs that convert primary solar and wind energy into electricity. Table 3 presents an overview of all RETs that are relevant for this study. This restriction is because of future plans for renewable electricity production in the Maldives is confined to the use of these particular applications [6,17].

All the systems under considerations are connected to a (mini) grid, because homes are usually very close to each other and grid extension is therefore not expensive. Usually, diesel generators with a comprehensive grid are already present. Furthermore system configurations that consist of more than two electricity generation components are

Table 3
RETs under consideration

Type	System	Source	Storage
Grid-connected	Wind Turbine(s)	Wind	Grid
(Malé)	Solar PV system	Sun	Grid
	Wind-diesel hybrid system	Wind, DFO	DFO, battery bank
Mini-Grid	Solar-diesel hybrid system	Sun, DFO	DFO, battery bank
(Outer islands)	Wind stand alone	Wind	Battery bank
	Solar stand alone	Sun	Battery bank
	Solar-wind hybrid system	Wind, Sun	Battery bank

excluded from this research. This is because several pilot projects in the past have shown that these systems (for example solar-wind-diesel hybrid), have caused operational problems, when they are the first system to be implemented. In the Pacific atolls, none of these systems have provided commercial power and none have survived more than a few years [18].

4. Optimization of RE based systems

In order to come up with a specific design for RE based systems presented in Table 3, this research makes use of the hybrid optimization model for electric renewables (HOMER version 2.19) [9]. For each hour in a year, the model compares the electric demand to the energy that the system can supply, and calculates the flows of energy to and from each component of the system. The design of these systems is such that it can meet the specific demand that the system must serve, while taking into account the load, the availability of resources and the variation in costs of technology.

4.1. Load characteristics

The load characteristics of the system are of great importance for the optimization of the system. For instance, if the peak load is demanded in the evening (due to lighting), it is impossible to use direct solar energy in order to meet this peak demand. On the other hand, the peak load could be partly met by a battery, which is charged during the day by the PV panels. The typical daily load patterns for Malé and one representative type of outer islands are presented in Fig. 2. Although the load curves within the outer islands do not differ that much, in comparison with Malé two major differences can be found. First of all the energy consumption per capita is almost 4 to 5 times higher than in the outer islands and second the load curve is more flattened, because of the high energy demand during office hours. This is mainly caused by the rapid penetration of air conditioning systems in Malé.

4.2. Resource assessment

The parts of the load that can be met by PV systems, or wind turbines depend on the availability of the solar and wind resources. Since hourly solar radiation and wind speed data are not yet available in the Maldives, it is necessary to generate synthetic hourly solar

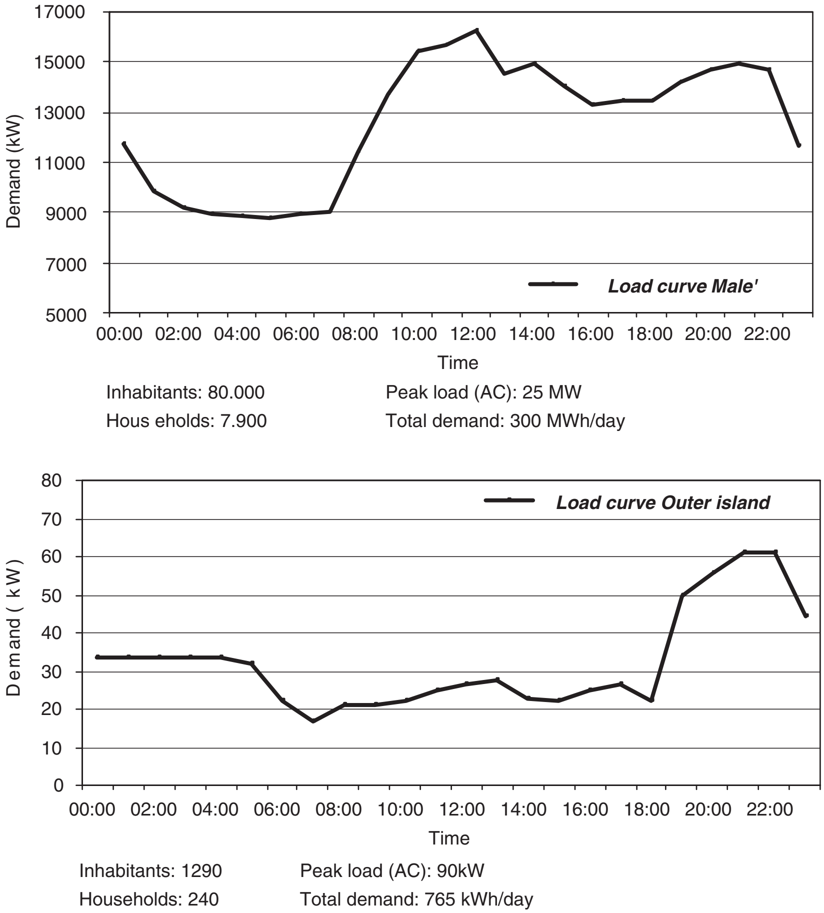


Fig. 2. Typical daily load pattern for Malé and the outer island of Hanimadhoo [18,34,35].

and wind data from monthly averages. The algorithm that is used to synthesize solar data is based on the work of Graham [19] and is implemented in HOMER.

Generating hourly wind data is more difficult than synthesizing solar data, because it requires more parameters. Besides the monthly averages, the most important parameter to generate hourly wind data is the Weibull k value, which is a measure of the distribution of wind speeds over the year. The Weibull k value is one of the two parameters of Weibull density function, which gives the probability of a certain wind speed during the year. The Weibull wind speed probability density function can be calculated as [20]:

$$p(v) = \left[\frac{k}{C}\right]\left[\frac{v}{C}\right]^{k-1} \quad \exp\left[-\left(\frac{v}{C}\right)^{k}\right], \tag{1}$$

where $p(v)$ is the probability of observing wind speed v, C is the Weibull scale parameter which indicates how 'windy' a wind location under consideration is and k is the dimensionless Weibull shape parameter and is used to calculate the wind speed distribution over the year. The shape factor will typically range from 1–3. For a given average wind

speed, a lower shape factor indicates a relatively wide distribution of wind speeds around the average, while a higher shape factor indicates a more narrow distribution of wind speeds (like tropical wind environments). A lower shape factor will normally lead to a higher energy production for a given average wind speed. This is because a wider distribution of wind increases the change of obtaining higher wind speeds and the energy content of high wind speeds is much larger than that of lower wind speeds, because the kinetic energy in the wind varies in proportion to the cube of the wind speed. Once the average ($\bar{v}$) and the variance (σ^2) of the wind speed data are known, the following approximation can be used to calculate the Weibull parameters C and k [20]:

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \quad (1 \leqslant k \leqslant 10), \tag{2}$$

$$C = \frac{\bar{v}}{\Gamma(1 + 1/k)}, \tag{3}$$

where the Γ function is defined as $\Gamma(x) = \int_0^\infty e^{-u} u^{x-1}\,du$. The average wind speed ($\bar{v}$) and the variance (σ^2) of the wind velocity recordings are

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i, \tag{4}$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(v_i - \bar{v})^2. \tag{5}$$

By using the average wind speed ($\bar{v} = 4.70\,\text{m/s}$) and variance ($\sigma^2 = 2.86\,\text{m}^2/\text{s}^2$) of the wind velocity that are obtained from hourly measurements[4] [21] the Weibull parameters k and C are determined to be 3 and 4.26 m/s, respectively, for the wind regime in the Maldives. This result is expected for the tropical monsoon type of winds that can be found in the Maldives [22]. The graphs in Fig. 3 show that the highest wind speeds are present during the northwest monsoon from May till October and that the lower wind speeds are obtained during the northeast monsoon in December and January.

The wind pattern of the monsoon and the solar irradiation in that period make an almost perfect match. During the windy monsoon periods the solar irradiation is lowest due to the overcast. Opposite, in the inter-monsoon periods there is a lot of sunshine and the wind density is low. Fig. 4 shows that the months of May and June have the least solar radiation, while high wind speeds have been measured in these months. Besides the monthly inputs, the orientation of the array and the latitude of the site are used to calculate monthly and annual average daily radiation in the plane of the photovoltaic array. With fixed-slope systems that are considered in this study, a slope roughly equal to the latitude will typically maximize the annual PV energy production.

4.3. Investment costs

The cost analysis is done to estimate costs associated with the different system configurations presented earlier. These costs are addressed from the initial, or investment,

[4] As a part of the RETDAP project (see footnote 2), wind speeds are measured hourly at three different wind zones in the Maldives since July 2003.

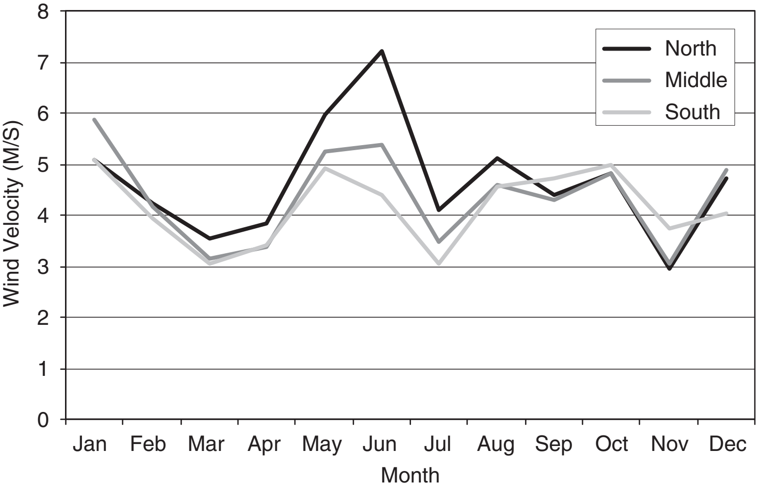


Fig. 3. Wind resource data in three different wind zones in the Maldives [36–38].

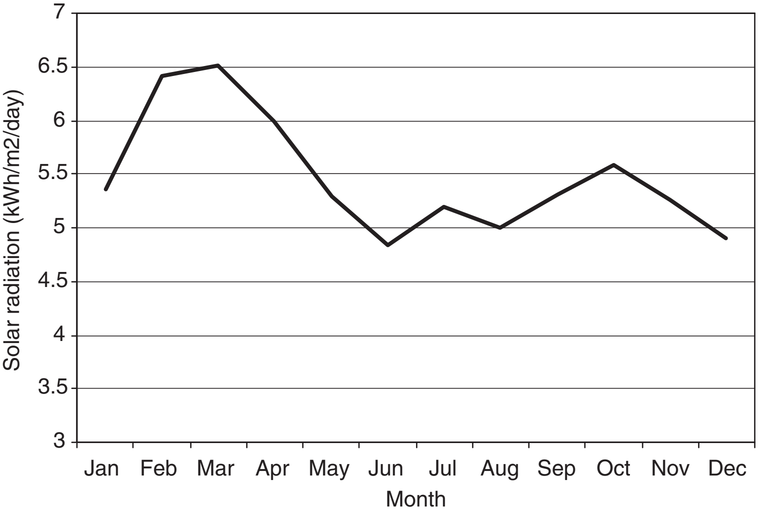


Fig. 4. Monthly solar radiation data [36–38].

cost standpoint and from the annual, or recurring, cost standpoint. The major categories for the initial costs include costs for training of operating personnel, completing the necessary engineering, purchasing and installing the RE equipment, construction of the balance of equipment (BOS) and costs for any other miscellaneous items. A detailed overview of the initial costs for RE projects is given in Table 4.

Table 4 shows that cost range of the different investment can be broad. E.g., the costs associated with the training of plant operators and maintenance personnel will depend on the size, complexity and remoteness of the installation. For isolated areas, there will be a greater need for local trained technicians in order to avoid lengthy repair delays. Besides

Table 4
Breakdown of investment costs for RE based systems (based on information from various manufacturers' quotes and [9,40,41])

	Cost range (US$)	Unit
PV—materials and equipment		
Solar panel	4200–6000	kWp
Mounting hardware	10–100	m^2
Control system	400–600	kWp
Wiring	200–400	kWp
Wind—materials and equipment		
Wind turbine (5–20 kW)	1500–2250	kW
Wind turbine (20–75 kW)	750–1500	kW
Wind turbine (75–200 kW)	500–750	kW
Spare parts	1–10	%
Control systems	600–800	kW
Wiring	200–400	kW
BOS—materials and equipment		
Battery bank	200–400	kWh
Charger/charge controller	40–50	kWh
Inverter/load controller	800–1500	kW AC
Generator (10–25 kW)	500–1000	kW
Generator (25–100 kW)	250–500	kW
Generator (100–250 kW)	150–250	kW
Other initial costs		
Engineering and development	500–3000	kW(p)
Installation	800–2000	kW(p)
Transportation	5000–25,000	project
Training	500–20,000	project

Table 5
Training costs for different RE system sizes (based on information from various manufacturers' quotes and [41])

System size	0–25 kW	25–75 kW	75–150 kW	150 < kW
PV	550	1650	3850	700
Wind	2000	8400	12,600	18,400

that, a wind-integrated system requires more training than a photovoltaic system, which is relatively easy to operate. And it might be clear that the operation of the system becomes more complex with the number of components integrated in the system and the size of the system. The training costs for the different system configurations are given in Table 5.

Furthermore the installation costs of a PV system are generally lower than integrated wind systems, but depend a lot on the type of mounting structure used; installing PV panels on rooftops in Malé would be more costly than a system that is mounted on the ground on an outer island. Cost differences can also be found in the equipment investments. For example, the total cost of the PV module depends on the total PV array power (kWp) output required, which is specified in the different system designs and the

price per kWp for PV modules. At present these prices per kWp differ from \$4200 to \$6000 per kWp, but due to learning processes these prices will most probably come down in the near future. Prices between \$3200 and \$4000 are expected by 2010 [23]. The price of a wind turbine is also expressed in terms of dollars per kW capacity, but unlike PV, which does not provide a significant reduction in generation costs with an increasing size of the systems, different sizes of wind turbines do produce power at different rates. Small systems generally generate electricity at higher cost than larger turbines.

4.4. Annual and periodic costs

The BOS for a wind/solar- diesel hybrid project typically includes the cost of the battery bank. The battery cost will vary depending on the type and size of batteries. Typical costs of lead acid batteries with a lifetime of 5 years are \$150 to \$225 per kWh. The price of batteries increases rapidly with the lifetime. The batteries throughput used in this study is approximately 12.000 kWh and should be replaced according to the intensity of its use during the lifetime of the project, which is assumed to be 20 years.

The annual costs associated with PV and Wind (hybrid) systems are likely to be relatively small compared to the overall system cost. For hybrid systems the cost of diesel fuel represents a substantial part of the annual cost. Besides the fuel costs in the case of a hybrid system where a genset is incorporated, the O&M costs of the PV and wind systems contribute the most to the annual costs. Generally speaking the O&M costs of a wind energy based system is twice as high as a PV system and is roughly 1 or 2% of the initial investment, but demonstration projects in the pacific islands have shown that the harsh tropical climate and the remoteness of the sites have lead to even higher maintenance costs for wind turbines. This had caused the failure of installations in French Polynesia, Fiji and several others in the northern pacific [18]. Wind electric systems that have survived for several years, as is the case for some installations in the French Territories, have not been producing electricity cost effectively, largely due to unexpectedly high maintenance costs [18]. Because of this pacific island experience the O&M costs of wind energy based systems is expected to be in the order of 4–5% of the equipment and material costs of a wind turbine. Usually the PV modules require less maintanence (e.g., occasional cleaning in dusty areas) and are assumed to be 1–2% of the equipment and material costs of the system. Components of a PV or wind system more likely to need maintenance are batteries and fossil-fuel generators in the hybrid systems (e.g., oil change).

5. Adoption of RETs

For each of the five common type of islands in the Maldives the probability of adoption of the optimized RE system configurations is assessed. The adoption of a new product or innovation is a decision process that moves through different stages over time, namely awareness, interest, evaluation, trial and adoption/rejection. If the decision is in favour of adoption, an implementation phase follows. Implementation is a critical period in the diffusion process since it requires action on the part of adopters to put the new idea into practice [24]. Question is; what makes an innovation successful? Innovation diffusion theory has identified five critical characteristics that are helpful in explaining this. Note that these are not requirements for a successful innovation, but their presence or absence could greatly affect the rate at which it will be adopted. In explaining the rate of adoption

of an innovation, Rogers [25] highlighted that five of the perceived attributes of an innovation are the main determinants explaining 49–87% of the variance in the rate of adoption. These five attributes are:

1. *Relative advantage*: which is the degree to which an innovation is better than the status quo. The degree of relative advantage is often expressed as *economic profitability*. However, three more determinants of relative advantage have been identified resulting from interviews with key-stakeholders in the Maldives and literature review. First; the mitigation of GHG gas emission (*sustainability*), second; social-economic development due to electrification (*social development*) and third; the utilization of indigenous energy sources (*renewable energy supply*), which reduces the dependency of imported fossil fuels [26–29].
2. *Compatibility*: which is the degree to which the innovations is consistent with existing values, past experiences and needs of potential adopters.
3. *Simplicity*: which is the degree to which the new technology is easy to understand and use.
4. *Trialability*: which is the degree to which an innovation may be experimented with on a limited basis.
5. *Observability*: which is the degree to which the results of an innovation are visible to others.[5]

5.1. Evaluation criteria

The attributes of innovation are used in this study as criteria that enable alternatives to be compared from a specific point of view. When either PV systems, or wind energy based systems obtain a high score on the different key characteristics of innovation, a high probability of adoption is expected, which is directly related to the potential of the RET under consideration. The evaluation criteria are operationalized as follows:

- The *profitability* is a straightforward criterion that is operationalized by the net present Value (NPV) of the project. The NPV is the value of all future cash flows, discounted at the real interest rate and is widely used as an indicator for the economical feasibillity of investments. A higher NPV indicates higher financial revenues and therefore a higher profitabillity. Positive NPV values are an indicator of a potentially feasible project and are calculated according to:

$$\mathrm{NPV} = \sum_{i=1}^{L} \frac{B_i - C_i}{(1-r)^i}, \tag{6}$$

where B_i are the total annual benefits[6] in year i and C_i are the total annual costs in year i, r is the discount rate and L is the lifetime of the project. Many activities consist of an initial investment I, followed by an annual net benefit B and cost C that are constant in

[5]Because the majority of the stakeholders that were interviewed for this study could not relate to this specific characteristic of the RET, it has been left out of the conceptual framework.

[6]The benefits represent income generated out of electricity sales against the average electricity prices in the years 2003/2004.

time. In that case the calculation of the NPV is highly simplified:

$$\mathrm{NPV} = \frac{B - C}{\alpha} I \tag{7}$$

in which the annuity factor is defined as

$$\alpha = \frac{r}{1 - (1 + r)^{-L}} \tag{8}$$

with L the project lifetime and r the real interest rate.

- The broad concept of *sustainability* is operationalized in a strictly ecological sense. For all the system configurations it is calculated by how much carbon dioxide emissions can be reduced. The more CO_2 reduction, the higher the sustainability of a certain RE system. The amount of carbon dioxide emissions (tCO_2) that can be reduced by implementing RETs is calculated using [6]

$$tCO_2 = 3.667 * m_f * HV_f * CEF_f * X_c. \tag{9}$$

In which m_f is the fuel quantity (liter), HV_f is the fuel heating value (MJ/l), CEF is the carbon emission factor (ton Carbon/TJ) and X_C is the oxidized carbon fraction. For diesel fuel oil the heating value is 38.99 MJ/l, the CEF is 20.2 tC/TJ and the oxidized carbon fraction is 0.99. The only factor in the equation that differs per RET alternative is the amount of supplanted fossil fuel by the system, which concurs with the *renewable energy supply*: Eq. (9) thus reduces to

$$tCO_2 = 3.667 * m_f * 38.99 * 20.2 \times 10^{-6} * 0.99 = 2.86 \times 10^{-3}. \tag{10}$$

- The *social development* is measured by the unit costs, or levelized costs of energy. This is the average cost of producing electricity. These production costs influence the price of electricity and a decrease of the electricity price leaves more room for the community to develop themselves, because they can start up more energy intensive businesses and spent their saved time and money on other goods and services. The lower the unit costs, the higher the social and economic development will be. The unit costs C_{lev} (\$/kWh) are the sum of the annualized costs of all the system components $C_{ann,tot}$ (\$/year) divided by the primary load E_{prim} that is served in that year (kWh/year).

$$C_{lev} = \frac{C_{ann,tot}}{E_{prim}}. \tag{11}$$

The annualized cost of a component is equal to its annual operating cost plus its capital and replacement costs annualized over the project lifetime. The annualized capital cost (C_{acap}) of each component is calculated using

$$C_{acap} = I \times \alpha \tag{12}$$

in which I is the initial investment and α is the annuity factor as defined in Eq. (8).

- *Renewable energy supply*: It has been argued before that the dependency on imported fossil fuels is a great concern in the Maldives and other SIDS. The utilization of indigenous energy sources creates less dependency on foreign countries and rising oil prices. The amount of diesel that is replaced by the different RE based systems is calculated according to

$$\mathrm{RES} = \mathrm{DC_{BCS}} - \mathrm{DC_{RES}}, \tag{13}$$

where RES is the RE supply, DC_{BCS} is the diesel consumption in the base case system and DC_{RES} is the diesel consumption in the proposed RE based system. The amount of diesel that is used in a system is calculated by dividing the annual energy output of the generator (kWh) by the efficiency of the system (L/kWh). Note that a 100% RE system does not require any DFO and that the saved DFO is equal to the amount of DFO that is consumed by the base case scenario.

- *Compatibility*: Many RE projects have failed, because good training on how to operate and maintain the system was not provided. [18,30] The costs associated with the training of plant operators and maintenance personnel will depend on the size, complexity and remoteness of the installation and is therefore a good indicator to determine the compatibility of the system.
- The costs for the operation and maintenance (O&M) of the system itself are used as an indicator for the *simplicity* of the system.
- *Triability*: is defined as the degree to which an innovation may be experimented with on a limited basis. The risk of investing in a relatively cheap technology, for example a few kWp solar panels is much lower than when you invest in a large off-shore wind farm. That is why the triability of the RET is operationalized by its investment costs (or initial costs). The height of the investment costs has a negative effect on the triability of the technology under consideration.

5.2. Multi criteria decision aid

In order to compare the different RE system configurations with each other and select the option that has the highest probability of adoption on a specified location in the Maldives a multi-criteria analysis is performed using the software package DEFINITE [10]. The calculated data shown in the evaluation matrices that will be drawn up are standardized and than weighted summation was used to rank the alternatives [10]. Usually, equal weight is given to the criteria, which are the seven discussed above. This leads to a certain probability of adoption. Trade-offs between objectives are usually politically motivated, therefore we additionally will show results on deliberately favouring one criterion over the other six. This is useful to demonstrate the relation between political priority and preferred choice.

6. Results

6.1. Technical design

One of the difficulties that come with the design of a stand alone, or hybrid RE systems, is the large number of variables to be considered, including the size of each of the components. Based on the load patterns, the technology costs and the resource data thousands of simulations have been performed for the five different case study islands, while varying the component sizes. For a specific island there will be an optimum design for the present load pattern. Using the information generated by the simulation runs, general design criteria have been developed for the main island of Malé and the four outer islands. The basic design criteria that can be applied to the integration of photovoltaics and wind turbines into the existing diesel generation systems, or the complete

Example 1: In the case of Uligam (the second largest of the four Outer island cases) the daily load is 178 kWh a day, with a peak load of 26 kW. Applying the general system criteria for a stand-alone system to this island, results in an inverter and rectifier (converter) capacity of 26 kW. Furthermore the PV panel should produce on average 178 * 1.66 = 295.5 kWh per day. From the available resource data the average solar radiation in the Maldives is 4.93 kWh/m². Thus one kWp of rated capacity can produce an average of 4.93 kWh/day times the derating factor of 0,9 = 4.43 kWh/day. (The derating factor is a scaling factor [typically less than or equal to 100%] applied to the PV array output to account for losses.) To produce an average of 295.5 kWh day, a total capacity of 295.5/4.43 = 67 kWp is needed. The battery should be able to provide electricity to the island community for at least 6 days, which is equal to a capacity requirement of 6 * 178 = 1068 kWh. In summery; the technical design for PV stand alone system on Uligam consists of a 26 kW converter, A 67 kWp PV panel and a battery bank with a capacity of 1068 kWh.

Example 2: The daily load of Fehendhoo (the smallest case study island) is 100 kWh a day, with a peak load of 13 kW. Applying the general system criteria for a solar-diesel hybrid system stated to this island results in a converter capacity of 4 kW (equal to ± 25% peak load, plus 20% excess capacity). The PV panel should produce on average 100 * 0.35 = 35 kWh per day. To produce an average of 35 kWh day, a total capacity of 35/4.43 = 8 kWp is needed. The battery should be able to provide electricity to the island community for at least 65% of the daily load, which is equal to a capacity requirement of 65 kWh.

Fig. 5. Examples of technical designs for two of the case islands.

supplementation of conventional systems by RETs are detailed below and they are applied in the examples given in Fig. 5.

6.1.1. Design criteria PV systems

General design criteria that provide the best techno-economic advantages for complete substitution of existing diesel systems by PV systems in the outer islands are found to be:

- The battery size should be sufficient to provide the system with at least six days of autonomy;
- There needs to be a three phase synchronized inverter with a capacity equal to the peak load;
- The battery charger should follow the optimum charge rate curve of the batteries with a capacity equal to the inverter.
- The total capacity of the PV array should be sufficient to carry the daily load; typically 5/3 of the total daily load should be installed.

For partly solar supplementation (30%) of existing diesel systems in the outer islands the general design criteria are found to be:

- The battery size should be sufficient to provide at least 65% of the daily load;
- The converter should have sufficient capacity to handle the off peak load plus at least 20% of excess capacity (the off peak load is around 25–30% of the peak load, see Fig. 2) and;
- The capacity of the PV panels should be sufficient to carry the off peak daytime load on a clear day, typically 35% of the daily load.

The main design restriction for PV systems connected to the grid in Malé lies in the availability of space to install the system. The capital of the Maldives is about 2 km long and 1 km wide, and is completely covered with roads, buildings and a few well-used open spaces. New building work is going on everywhere and the future of PV in Malé can be found on the rooftops of these new and old government and office buildings. It is assumed that the area of rooftops that is suitable for a PV installation has a maximum of 1% of the total land area in Malé, which leads to a total suitable area of 20 000 m^2. The direct solar radiation in Malé has an average above 0.2 kW/m^2. So a system with 100% efficiency will produce an average of 4000 kW. As actual PV system efficiency is about 12.5% [31], the average capacity of the system will be 500 kW.

6.1.2. Design criteria wind systems

It is not possible to make a general design for wind energy based systems, because the different sizes of wind turbines that are used in the analysis produce power at different costs. In addition, unlike solar systems, where the power output is linear with the installed capacity, the power output of a wind turbine depends on its specific design. For example a small wind turbine usually has a lower "cut in" wind speed, which means that it already produces electricity at a wind speed whereby a larger turbine does not generate any electricity at all. On the other hand the energy output of larger turbines will increase more rapidly at higher wind speeds than smaller ones. In this study seven different commercial systems have been compared for each of the case study islands; ranging from 6 kW rated power to 250 kW. For each case these wind turbines have been modelled and an optimum design is created. The battery size depends mainly on the excess of electricity produced by the turbine and the efficiency of the current diesel generator (in hybrid systems). The battery bank is designed in such a way that the generator will only run at efficiencies by which the costs of fuel does not exceed the costs of extra battery capacity.

6.2. Evaluation matrix

Table 6 shows how the various RE based systems perform on the basis of the different assessment criteria. Compared to current electricity prices of US$ 0.3–0.5/kWh (i.e., base case in Table 6) on the outer islands, it is clear that all optimum hybrid options, i.e., wind-diesel and solar-diesel are economically feasible. Table 6 further shows that due to the higher RE fraction in the wind-diesel configurations more diesel is saved compared to solar-diesel configurations resulting in lower GHG emissions. The NPVs also show that none of these 100% renewable system configurations are economically feasible, especially the wind stand-alone systems. This is because they are designed in such a way that it can meet the electricity demand in the inter-monsoon period, where strong winds are rare. This causes the large excess of electricity that is produced in monsoon periods. This surplus of electricity that is produced can be seen as a loss of income and makes the projects less profitable and causes high unit costs. Note that a wind-solar hybrid system is economically more feasible than a solar, or wind stand-alone systems, because of the match between the wind patterns of the monsoon on the solar irradiation. During the windy monsoon periods the energy output of the solar panels is low due to the overcast. Opposite to this, in the inter-monsoon periods there is a lot of sunshine and wind speeds are low.

In most hybrid configurations, which are already cost-efficient, excess of electricity is generated. This indicates that the profitability of these systems can be even higher if the

Table 6
Key results from HOMER simulations of the base case- and optimal RE system configurations for the Outer islands

Scenario	Parameter	Unit	Island 1	Island 2	Island 3	Island 4
Base case	Electricity demand	MWh/yr	37	65	111	280
	Unit costs	\$/kWh	0.38	0.39	0.35	0.26
Optimum solar-diesel hybrid system	RE-fraction	%	30.2	30.4	30.1	30.0
	Excess electricity	MWh/yr	4.7	11.0	18.9	44.9
	Fossil fuel savings	1000L/yr	14	18	28	32
	Emission reduction	tCO_2/yr	40	51	81	93
	NPV (IR 5%)	1000\$	50	51	28	−149
	Capital costs	1000\$	55	130	202	508
	Annual costs	1000\$/yr	6.6	12.8	22.2	47.4
	Unit costs	\$/kWh	0.29	0.34	0.33	0.30
Optimum wind-diesel hybrid system	RE-fraction	%	69	46	57	75
	Excess electricity	MWh/yr	14.3	10.9	33.8	141.8
	Fossil fuel savings	1000L/yr	19	21	39	64
	Emission reduction	tCO_2/yr	56	59	112	182
	NPV (IR 5%)	1000\$	16	66	67	86
	Capital costs	1000\$	85	96	169	377
	Annual costs	1000\$/yr	6.9	14.2	21.8	40.2
	Unit costs	\$/kWh	0.35	0.32	0.30	0.24
Optimum solar-wind hybrid system	RE-fraction	%	100	100	100	100
	Excess electricity	MWh/yr	70.0	77.0	90.8	467.6
	Fossil fuel savings	1000L/yr	25	37	63	98
	Emission reduction	tCO_2/yr	73	106	180	280
	NPV (IR 5%)	1000\$	−320	−457	−708	−2607
	Capital costs	1000\$	332	560	898	2445
	Annual costs	1000\$/yr	13.1	18.3	25.1	84.0
	Unit costs	\$/kWh	1.00	0.89	0.80	0.91
Optimum solar stand-alone system	RE-fraction	%	100	100	100	100
	Excess electricity	MWh/yr	29.2	48.7	80.8	206.0
	Fossil fuel savings	1000L/yr	25	37	63	98
	Emission reduction	tCO_2/yr	73	106	180	280
	NPV (IR 5%)	1000\$	−379	−555	−1019	−2822
	Capital costs	1000\$	435	694	1188	2898
	Annual costs	1000\$/yr	10.0	15.8	26.5	67.3
	Unit costs	\$/kWh	1.11	0.99	0.99	0.97
Optimum wind stand-alone system	RE-fraction	%	100	100	100	100
	Excess electricity	MWh/yr	105.0	180.8	525.2	840.8
	Fossil fuel savings	1000L/yr	25	37	63	98
	Emission reduction	tCO_2/yr	73	106	180	280
	NPV (IR 5%)	1000\$	−454	−794	−764	−2841
	Capital costs	1000\$	396	723	803	2368
	Annual costs	1000\$/yr	18.0	32.0	35.6	105.8
	Unit costs	\$/kWh	1.26	1.29	0.83	0.97

surplus of renewable electricity is utilized for other purposes, like water desalination, flake ice production (for fish cooling), pumping of water, or heating. One can even contemplate generation of hydrogen for fuel-cell electric vehicles. The economic revenue gained from

these activities can eventually bring down the production costs of electricity and induce socio-economic development.

It is also worth noting that the system hybrid configurations, that include a wind turbine, become more feasible when the island size increases. This is not the case for the solar-diesel hybrid systems, because of the modular character of solar panels that show no relative reduction in investment costs as the installed capacity increases. That is why hybrid configurations that include photovoltaics are only financially feasible on smaller islands. Although more DFO is saved in the wind configuration, the overall costs are still higher. Besides the higher investment costs, this is mainly caused by more expensive O&M requirements and training of staff. Both systems provide cheaper electricity than the base case system in the smaller Outer islands, where generators are operated at low efficiencies. This is in contrast with the state of the art 30 MW power plant in Malé, which runs with a relatively high efficiency compared to the smaller generators in the outer islands. Therefore, electricity tariffs are lower in Malé and vary from US$ 0.18 for small consumers to US$ 0.25 for businesses [14].

Table 7 shows that both RE systems could be integrated into the grid without an increase in the unit costs. This is because the RE fraction of electricity that is generated by the PV systems is so small ($<1\%$) compared to the total amount of electricity that is produced in Malé, that the higher costs of the RE fraction have no influence on the price. But because of the negative NPV, there is no profit to be gained when implementing such a system. On the other hand, a wind farm on the coastline of Malé, would bring down the costs of electricity in the capital city. Despite the high investment and O&M costs, a wind energy based project connected to the utility grid is a profitable option. This is partly caused by the absence of batteries. In the case of Malé, the grid acts as a storage medium. The other important advantage of this system compared to the wind energy projects in the Outer islands, is that there is no excess of electricity produced by the wind turbines. All the electricity is utilized, which means that the economic benefits are at maximum in this system configuration.

The small RE fraction in the grid connected RE systems in Malé just exceed 5% of the total amount of electricity that is produced in the capital. The largest share of this electricity generated by RE sources comes from wind energy. And although a RE fraction of 5% sounds small, in terms of reduced CO_2-emissions, large quantities can be obtained (3795 ton/yr). The GHG-emission reductions are, for example, 13–40 times larger compared to the RE system configurations designed for the island of Hanimaadhoo (Island 4).

6.3. Multi criteria decision analysis

The various RE system configurations are compared using a multi-criteria analysis, in which the criteria defined above are used. The calculated data shown in the evaluation matrices (Tables 6 and 7) are standardized and than weighted summation was used to rank the alternatives. The overall performance of the alternative system configurations on the Outer islands and Malé are presented in Figs. 6 and 7 for different weighting choices.

Fig. 6 shows that if equal weight is given to the seven criteria, the wind-diesel hybrid is the preferred alternative for the Outer islands in terms of the seven criteria used. In general the probability of adoption is relatively high for wind-diesel and solar-diesel hybrid systems and low for 100% renewable system configurations. For Malé grid-connected

Table 7
RE system configuration, energy output, costs and financial feasibility of solar and wind on-grid systems in Malé

Alternatives system configuration	Unit	PV-grid	Wind-grid
PV panels (+inverter)	kWp	250	–
Wind Turbines	kW	–	15 × 250
Grid (maximum demand)	MWh	25	25
Energy output			
PV panels	MWh/yr	886	–
Wind Turbine	MWh/yr	–	5105
Grid	MWh/yr	108,114	103,895
RE fraction	%	0.81	4.68
Diesel savings	1000 L/yr	230	1.327
Emission reduction	tCO_2/yr	659	3795
Cost parameters			
Total investment	1000$	5172	7195
Annualized (IR 5%)	1000$	363	504
Training	1000$	7.7	18.4
O and M	1000$/yr	54	338
Financial feasibility			
NPV (IR 5%)	1000$	−3151	4023
Unit costs	$/kWh	0.18–0.30	0.18–0.29
(RE fraction)	$/kWh	0.47	0.16

wind energy is preferred above photovoltaics even though the latter alternative obtains high scores on the criteria compatibility, simplicity and trialability.

As political choices may differ per stakeholder, an analysis is performed in which varying weights are associated with various criteria. Fig. 7 shows the results if priority is given to the various objectives/criteria. In each row priority is given to one objective: in the first row a weight of 50% is given to sustainability, the second row to profitability etc. This figure is useful to demonstrate the relation between political priority and preferred choice. In this example the wind-diesel system ranks first if priority is given to profitability, social development, and trialability. The solar-diesel configuration on the other hand scores better if priority is given to compatibility and simplicity. This could be a relevant choice in case of foreign development programs, whereby the success of a project is more important than profits. However, this alternative ranks last if priority is given to sustainability, or renewable energy supply.

7. The national potential of RETs

Now the optimum system designs for the outer islands and the capital Malé are known, it is possible to put these results in a national perspective. Therefore, it is assumed that the optimum hybrid system designs are implemented on the outer islands that are represented by the four study islands. In this way the maximum share of RE-based systems in the energy supply mix can be obtained. When solar-diesel hybrid systems are installed on the smaller Outer islands, represented by Fehendhoo, 30% of the electricity production comes

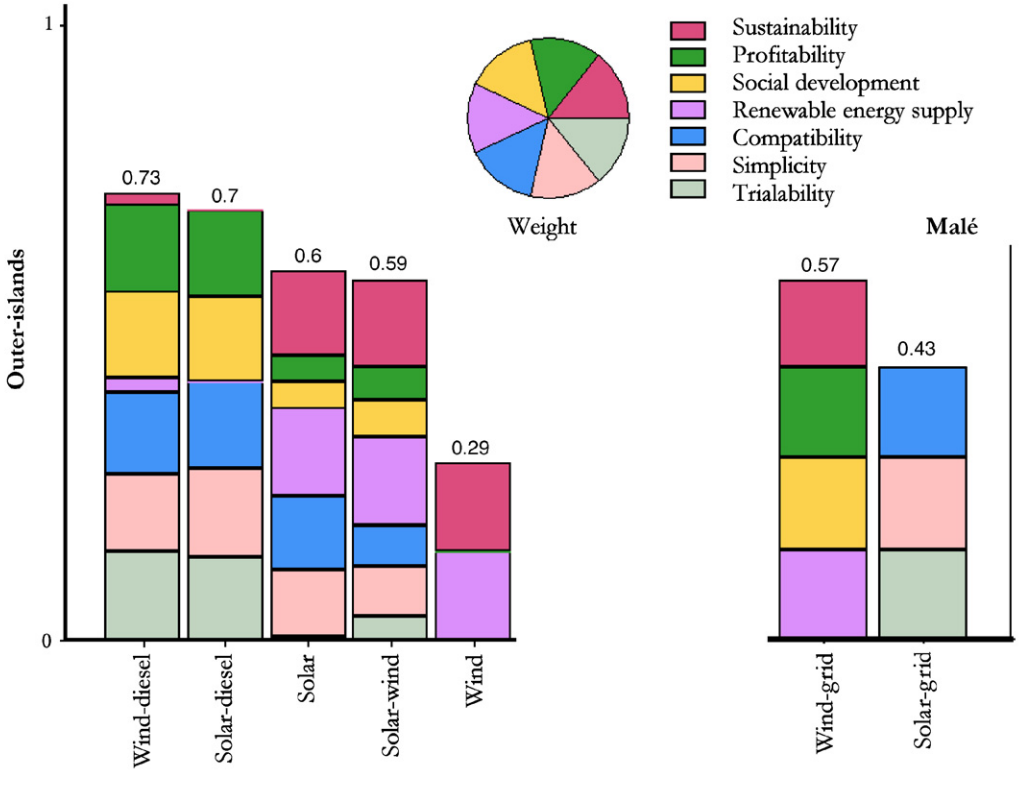


Fig. 6. Multi criteria analysis of the RET alternatives for the outer islands and Malé.

from RE energy sources. The fraction of wind energy that is utilized on the other 80% of the outer islands ranges between 55 and 65%. This concurs with 1.5 MWp of installed capacity PV and about 10 MW of wind energy. Together, they can supplant approximately 50% of the installed capacity in the outer islands. If the optimal system for Malé is implemented approximately 5.5% of the generated electricity in the capital comes from RE sources (Fig. 8), which amounts to 1.7 MW. Together with the RETs implemented in the outer islands they represent about 10% of the countries electricity generation capacity of 125 MW. Knowing that nearly half of the countries installed capacity is installed in resort islands, gives that at least 20% of the countries capacity in the inhabited islands can be supplanted by RE based technologies, keeping in mind that there is still a large potential for RE in the main islands and resorts, which were not included in this research.

8. Conclusions and discussion

In this article we first designed and subsequently evaluated several RE based systems in the Maldives regarding their probability of adoption. The evaluation shows that wind- and solar-diesel hybrid systems have a higher probability of adoption than 100% renewable system configurations. The latter systems are not financially viable in the Maldives. A wind-diesel hybrid system is in most cases more feasible than a solar-diesel system. The

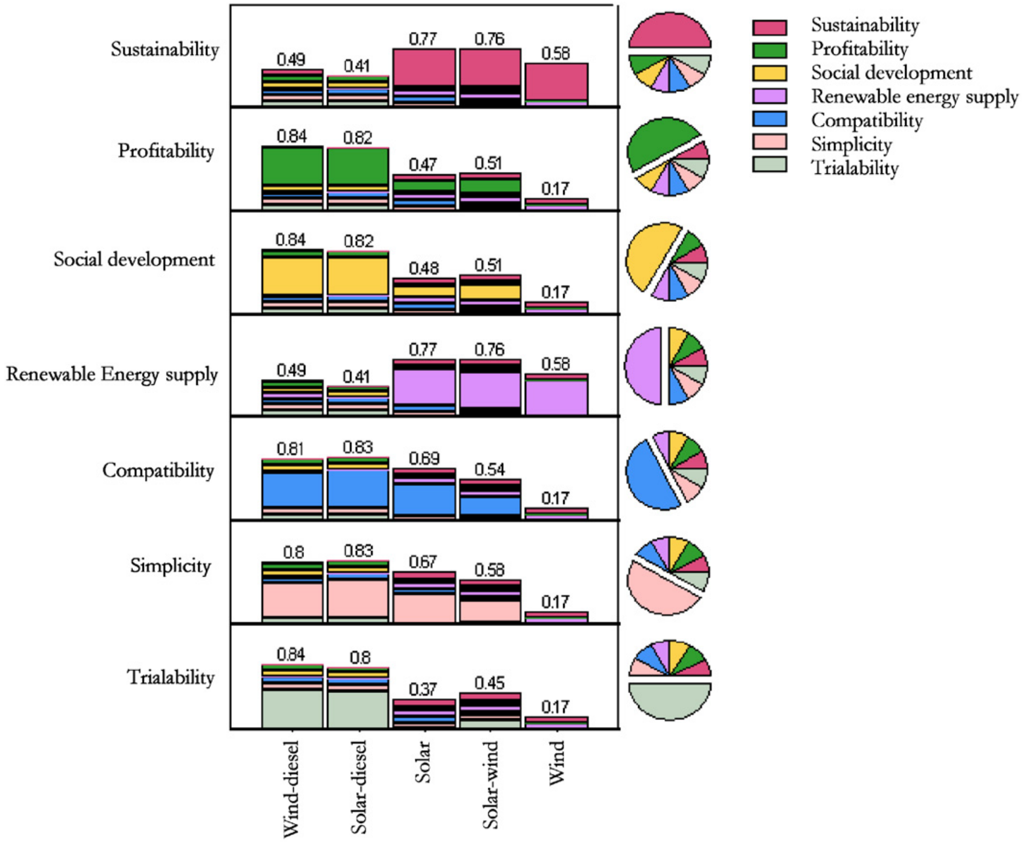


Fig. 7. Performance of alternatives according to policy priority.

amount of CO_2-emissions that can be reduced by implementation of such a system is also higher, because the RE fraction is larger in wind-diesel configurations. A solar-diesel hybrid system on the other hand is easier to operate and requires less training of personnel, which makes the technology more compatible.

Assuming that the optimal systems are implemented, the results show that 10% of the electricity the Maldives could be supplied by RE based systems in an economically viable way. This is rather high if you take into account that the energy intensive resort islands, which are responsible for nearly half of the countries energy consumption, were excluded from this research.

In order to obtain a more accurate result on the viability of RETs in the whole of the Maldives it is imperative to include the resort islands and make a comprehensive feasibility study of the Main islands (>1250 citizens) as well, as they account for 11% of the installed electrical capacity in the Maldives. Another point of discussion is the decision not to give an economic value to the excess of electricity that is produced by the systems. This would have made the different technological alternatives more financially feasible and it would have made the comparison between 100% RE systems and RE-diesel hybrid systems more fair for smaller islands. Also an additional study on inclusion of applications in the systems

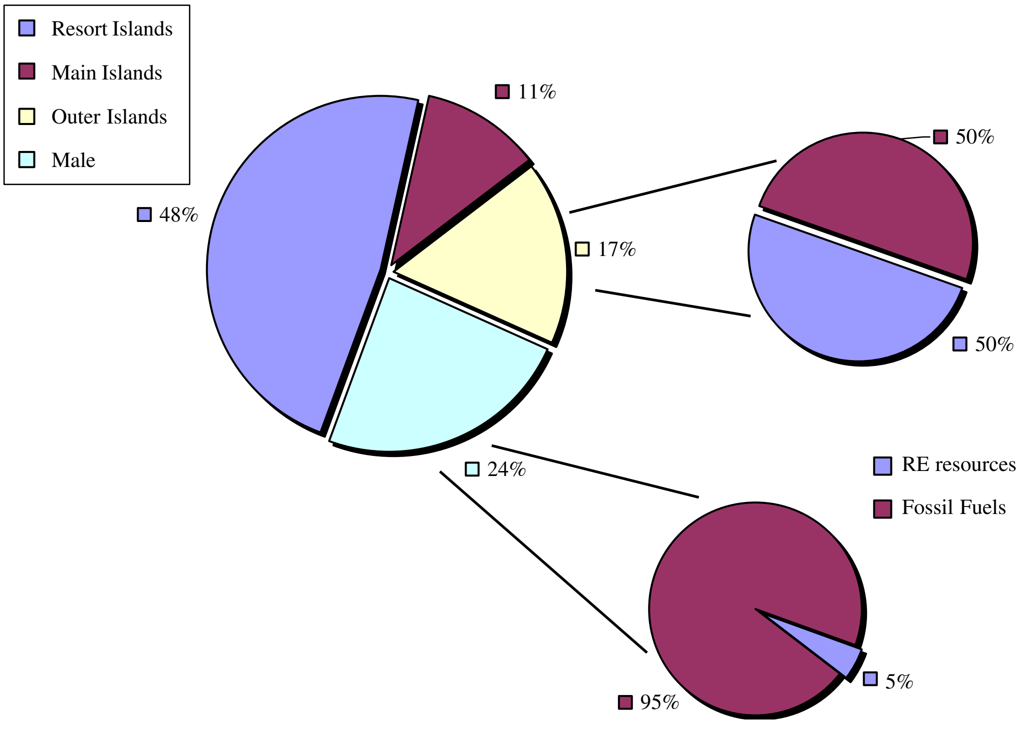


Fig. 8. Relative breakdown of installed capacity in the Maldives divided by energy source.

that utilize the electricity surplus (e.g. a water desalination plant) or on alternative storage mediums [32] would be of interest. For example, hydrogen could be produced by means of electrolysis in times when an electricity surplus exists and it could be converted back into electricity at times when electricity is needed (peak load) by means of fuel cells, however at the expense of a lower overall system efficiency.

Despite the shortcomings of this research, it is clear that a large potential exists for wind turbines around Malé and for solar- and wind diesel hybrid systems in the Outer islands. However, a technology with a high probability of adoption will not automatically be implemented as a result of the fact that the technology diffusion process is not only depending on the attributes of the technology itself, but also is influenced by various social, institutional and political factors. The concept of innovation systems (IS) integrates these elements into a comprehensive approach to RET transfer and is therefore used as a tool to analyse the diffusion process of RETs in the Maldives: it will be presented in the accompanying paper [7].

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References

[1] Weisser D. Power sector reform in small island developing states: what role for renewable energy technologies? Renewable Sustainable Energy Rev 2004;8:101–27.
[2] United Nations Economic and Social Council. Sustainable development of energy resources in small island development states. Report E/CN17/1996/20/Add.2. New York: United Nations; 1996.
[3] Mayer PC. Reliability economies of scale for tropical island electric power. Energy Economics 2000; 22(3):319–30.
[4] Corden WM. Framework for analysing the implications of rice in oil prices. Int Library Critical Writings Economics 2000;119(1):86–98.
[5] MHAHE. First National communication of the republic of Maldives to the United Nations framework of climate change. Malé: MHAHE; 2001.
[6] UNDP Republic of Maldives. Maldives: renewable energy technology development and application project. MDV/03/G35/A/1G/99 (GEF) Malé: UNDP Republic of Maldives; 2004.
[7] Van Alphen K, Hekkert MP, van Sark W.G.J.H.M. Renewable energy technologies in the Maldives—realizing the potential, Renewable and Sustainable Energy Reviews; 2006 [submitted for publication].
[8] Painuly JP. Barriers to renewable energy penetration, a framework for analysis. Renew Energy 2001; 24:73–89.
[9] NREL. HOMER version 2.19, National Renewable Energy Laboratory (NREL) URL. 〈http://www.nrel.gov/homer〉; 2005.
[10] Janssen R, van Herwijnen M, Beinat E. DEFINITE for Windows. A system to support decisions on a finite set of alternatives (Software package and user manual). Amsterdam, The Netherlands: Institute for Environmental Studies (IVM), Vrije Universiteit; 2001.
[11] MPND. Statistical yearbook of the Maldives 2003. Malé: MPND; 2003.
[12] UN-ESCAP. Defining the structures of a national energy agency in the Maldives. Report for the UN-ESCAP advisory commission by Brahmanand Mohanty. Bangkok: UN-ESCAP; 2003.
[13] ECN. Technical report: energy supply and demand Project INT/99/R11—02 MDV 1180. Copenhagen: Energy Consultancy Network; 2004.
[14] STELCO. Status of power supply in Malé. Presentation STELCO, by Mohamed Latheef on Asia Pro Eco Kick Off Workshop, Malé, May 2004; 2004.
[15] EIA. World crude oil prices URL: 〈http://tonto.eia.doe.gov/dnav/pet/hist/wtotworldw.htm〉; 2005.
[16] EIA. Weekly Petroleum Status Report. URL: 〈http://www.eia.doe.gov/oil_gas/petroleum/data_publications/weekly_petroleum_status_report/wpsr.html〉; 2005.
[17] SMILES. Promoting renewable energies in the island context: sharing the European experience URL: 〈http://www.mcst.gov.mv/projects/smiles〉;2005.
[18] ADB. Preparing the Outer Island electrification project Draft report volume 4: Renewable Energy TA No 3232-MLD. Samoa: John Worrell; 2000.
[19] Graham VA, Hollands KGT. A method to generate synthetic hourly solar radiation globally. Solar Energy 1990;44(6):333–41.
[20] Weisser D. A wind energy analysis of Grenada: an estimation using the 'Weibull' density function. Renewable Energy 2003;28(11):1803–12.
[21] Lysen EH. Preliminary analysis wind and output data in the Maldives. Malé: MCST; 2004.
[22] Lysen EH. Introduction to wind energy. Eindhoven: SWD/CWD; 1983.
[23] Schaeffer GJ, Alsema E, Seebregts A, Beurskens L, de Moor H, Van Sark W, et al. Learning from the sun Analysis of the use of experience curves for energy policy purposes: the case of Photovoltaic Power. Final

Report of the Photex-project, Report ECN-C–04-035. Petten, the Netherlands: Energy research Centre of the Netherlands; 2004.
[24] Kendall J, Tung LL, Chua KH, Ng CHD, Tan SM. Electronic commerce adoption by SMEs in Singapore The Centre for Improving Teaching Effectiveness. Nebraska: Wayne State College; 2001.
[25] Rogers EM. Diffusion of Innovations, 4th ed. New York: The Free Press; 1995.
[26] Weisser D. On the economics of electricity consumption in small island developing states: a role for renewable energy technologies? Energy Policy 2004;32:127–40.
[27] Alves LMM, Costa AL, Carvalho MD. Analysis of potential for market penetration of renewable energy technologies in peripheral islands. Renewable Energy 2000;19:311–7.
[28] United Nations Economic and Social Council. Progress in the implementation of the programme of action for the sustainable development of small island developing states: sustainable development of energy resources in small island developing states E/CN17/1999/6/Add.12. New York: United Nations; 1999.
[29] Goldemberg J, Johansson TB. Energy as an Instrument for Socio-Economic Development. New York: UNDP; 1995.
[30] Jafar M. Renewable energy in the South Pacific—options and constraints. Renewable Energy 2000;19:305–9.
[31] IEA. International Photovoltaic Power system Programme (PVPS) URL: 〈http://www.iea-pvps.org/〉; 2004.
[32] Duic′ N, da Graça Carvalho M. Increasing renewable energy sources in island energy supply: case study Porto Santo. Renewable and Sustainable Energy Rev 2003;8:383–99.
[33] MAA. Status of electrification in the Outer islands. Presentation MAA on Asia Pro Eco Kick Off Workshop, Malé, May 2004; 2004.
[34] STELCO. Projects Planning and IT department: load curves State Electric Company Limited, Malé; 2003.
[35] Transénergy Maldives: Pre-feasibility study for hybrid system implementation in Fehendhoo and Fulhadhoo islands. Consultancy Report Paris: Transénergy; 2004.
[36] NREL. wind and solar resource assessment of Sri Lanka and the Maldives. Golden, Colorado: National Renewable Energy Laboratory; 2003.
[37] ECN. Design and specifications of pilot hybrid system. Project INT/03/R11—03 MDV 1180. Copenhagen: Energy Consultancy Network; 2004.
[38] NASA. Surface meteorology and Solar Energy. URL: 〈http://eosweb.larc.nasa.gov/sse/〉; 2004.
[39] STELCO. Status of power supply in Malé. Presentation STELCO, by Mohamed Latheef on Asia Pro Eco Kick Off Workshop, Malé, May 2004; 2004.
[40] Rehmana S, El-Aminb IM, Ahmada F, Shaahida SM, Al-Shehrib AM, Bakhashwainb JM, Shasha S. Feasibility study of hybrid retrofits to an isolated off-grid diesel power plant. Renewable and Sustainable Energy Reviews 2005;x:1–19.
[41] RETscreen International. Clean energy project analysis: RETscreen engineering and cases textbook. Catalogue no.: M39-99/2003E-PDF Ottowa: Ministry of Natural Resources Canada; 2001.